

ELECTRONIC FUNDAMENTALS

THEORY LESSON 32

WAVE PROPAGATION AND ANTENNAS

32-1. Electromagnetic Waves

32-2. Ground Waves

32-3. Sky Waves

32-4. Generalized Antenna Theory

32-5. A-M Broadcast-Band Receiving Antennas



RCA INSTITUTES, INC.

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Theory Lesson 32

INTRODUCTION

Have you ever tried to listen to a radio receiver or watch a television set that had been disconnected from its antenna? If you have, you probably remember that the signal (if you could hear or see it at all) was so weak that you could hardly understand and enjoy it. The function of a receiving antenna is to obtain as much energy from passing radio or television waves as is required for good reproduction of the desired signals. At the same time, the antenna system must have enough signal gain to overcome the static and other electrical noises that are radiated from sources nearby and received with the desired signal voltage. The picked-up signal must also exceed the noises generated in the receiver's components.

This lesson discusses wave propagation (transmission) and the part played by the receiving antenna in the reception of a radio signal. You will learn about a number of different types of receiving antennas, how they work, and when they are used.

32-1. ELECTROMAGNETIC WAVES

In order to understand the principles of receiving antennas, you must understand more about electromagnetic waves. The theory of electromagnetic waves is almost one hundred years old. In 1864, an English scientist, James Clark Maxwell, said that light, traveling from its source to the point where it is seen, is made up of an electric and a magnetic field, both in motion. These moving fields are at right angles to each other and contain equal amounts of energy. Together, these fields make up electromagnetic waves. Maxwell predicted that there must be electromagnetic waves other than light waves. In 1887, a German scien-

tist, Heinrich Hertz, showed that electromagnetic energy could be sent out into space in the form of radio waves.

You have already learned that a wire carrying an electric current sets up an induction field and know that the induction field collapses and falls back into the wire when the current goes from its maximum point to zero. If it were necessary to induce a voltage into the receiver antenna circuit by means of such waves, it would be necessary for the receiver to be very close to the transmitter. Either this or the transmitter would have to use tremendous amounts of power in its antenna circuit in order to induce a voltage in the antenna circuit of a receiver a few miles away, because the induction field varies inversely as the *square* of the distance. So, it is not by electromagnetic induction that we are able to produce a signal voltage in the antenna circuit of a receiver many miles distant from the transmitter. Yet we know that the signal is transmitted and received.

Wave Radiation. From experiments, we have found that when the induction field collapses, not all of the energy is returned to the conductor. Instead, what is called the *radiation* field breaks off from the conductor and travels out in space in the form of electromagnetic waves. These fields cannot be seen, although we know that they exist. The relative amount of energy that is radiated is very small at low frequencies but becomes greater as the frequency rises. Also, if the length of the conductor is electrically one-half wavelength, or even one-quarter wavelength, a considerable amount of energy is radiated. However, at low frequencies (under 20 kc), the length of a half-wave conductor would be very long. For example, to radiate a signal at 20 kc, the minimum length would have to be about five miles. Because the

physical length of the radiating antenna is a problem at low frequencies, and because of other reasons to be discussed, higher frequencies are used.

At r-f frequencies, the power radiated by a well-designed transmitting antenna is very high. In fact, practically all of the power delivered by the transmitter to the antenna is radiated. Usually, the only power not radiated is dissipated in the resistance of the antenna circuit.

Figure 32-1 shows a birds-eye view of a vertical transmitting antenna radiating a signal wave. Because the radiated wave is electromagnetic in nature, it has an electrical field and a magnetic field, each of which contains half of the energy that is radiated. Each of the concentric circles moving out from the vertical antenna represents the combined electromagnetic field produced by the signal at some point in its cycle. Each has been stopped at an instant in its travel away from the antenna. We call each of these circles a *wave front*. Because we are looking directly down at the antenna, we see these wave fronts as circles without any other dimension. Note that one segment of the outer wave front is drawn darker than the rest. Let's cut it out of the wave front and see what a segment of the wave front looks like when viewed from a different angle.

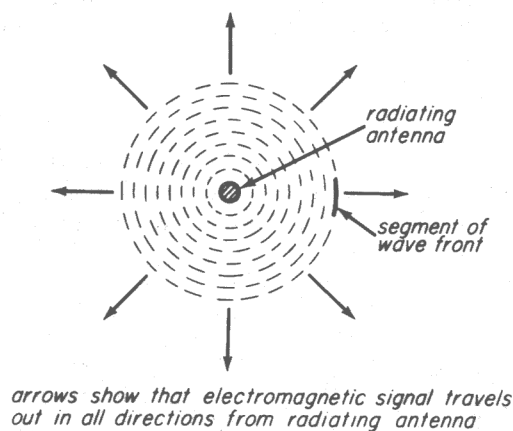
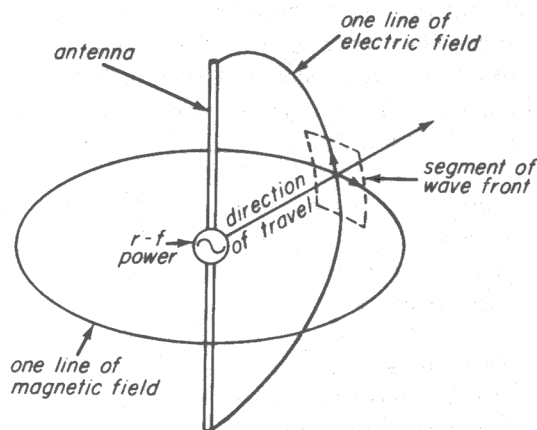


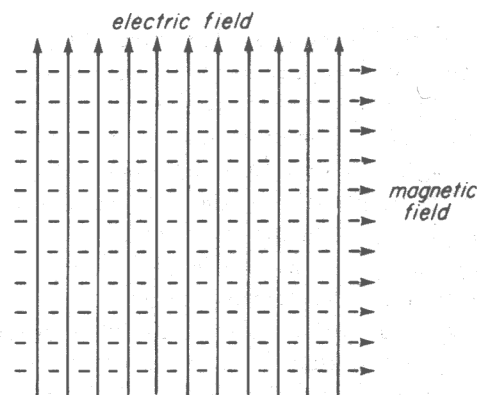
Fig. 32-1

Figure 32-2a shows signal power applied to the transmitting antenna, a segment of the wave front, the direction of travel of the wave front, and the instantaneous directions



segment of wave front traveling away from antenna

(a)



(b)

Fig. 32-2

(polarities) of the electric and magnetic fields of the wave front. Note that the electric field and the magnetic field are at right angles to each other and to the direction of travel. If the fields were visible and if we were to place ourselves between the transmitting antenna and the wave front segment so that we could see the wave front traveling directly away from us, we would see it as it is shown in Fig. 32-2b. From this point of view, we would see very little curvature; in fact, if we were any distance from the transmitter, the wave front would seem to be in a plane. The direction of each field reverses for each succeeding alternation of the signal.

Polarization. The electric field shown in Fig. 32-2 is vertical while the magnetic field is horizontal. By definition, when the electric field is vertical, the entire electro-

magnetic field is said to be vertically polarized. This is because the transmitting antenna is vertical. For the most efficient reception, the receiving antenna should be vertical, too.

A transmitting antenna that lies in a horizontal plane radiates a signal whose electric field is horizontal and whose magnetic field is vertical and is best received by a horizontally-polarized antenna. From this you can see that a signal radiated by a vertical antenna, should be received on a vertically polarized antenna, and one radiated by a horizontal antenna should be received on a horizontally polarized antenna. Later in this lesson, we'll see why this is important.

Field Intensity. The strength of a radio wave, or *field intensity*, is a measure of the strength of the electric field. This is usually expressed in microvolts per meter. It is the voltage induced in a conductor that is one meter in length, when this conductor is in the direction of the electric field and at right angles to the magnetic field and to the direction of travel. Suppose that a given radio wave induces a voltage of 20 microvolts in an antenna that is one meter in length. We say that the field intensity of the radio wave is 20 microvolts per meter. If the antenna were made longer, say 5 meters, the same radio wave would induce 100 microvolts, because the field intensity is 20 microvolts for *each* meter (20 microvolts per meter multiplied by 5 (meters) equals 100 microvolts). As the distance between the transmitting and receiving antennas becomes greater and greater, the field intensity of the radio wave *falls off* proportional to the distance. If the field intensity at a distance of 100 miles is 20 microvolts per meter, at 200 miles it may be 10 microvolts per meter. This simple fact helps us to realize two things; first, that the received signal has a field intensity that depends upon its distance from the transmitter, and second, the length of an antenna determines the voltage induced in it for a signal of given field intensity.

32-2. GROUND WAVES

The radiation of electromagnetic waves into space by a transmitting antenna, as you

know, is called wave propagation. We study wave propagation to find the different paths that radio waves may take. One of the main paths taken by radio waves is the *ground-wave* path. The ground wave travels from transmitter to receiver in a direction parallel to the surface of the earth. Short-distance transmission and all very-high and ultra-high frequency propagation take place by means of the ground wave.

The ground wave includes all types of radio transmission that do not make use of reflections from the ionosphere.

Ground waves may follow several paths in traveling from the transmitter to receiver, as shown in Fig. 32-3. They may take a direct path, they may be reflected from the surface of the earth, they may follow the curvature of the earth, they may go up in the air and be returned to earth by a process known as *refraction*. (Refraction is the bending of the waves when they pass from a medium of one density to a medium of a different density.) The difference in density in this case is caused by adjacent layers of air of different temperatures. Because this refraction occurs in the lower atmosphere, or troposphere, we speak of the path taken by refracted ground waves as the *tropospheric path*. The ground wave that actually reaches the antenna can be considered as being composed of one or more of the following components; the direct wave, the ground-reflected wave, and the refracted tropospheric wave.

Direct Wave. The direct wave travels directly from transmitting to receiving antenna without coming into contact with the ground. It travels from the transmitting

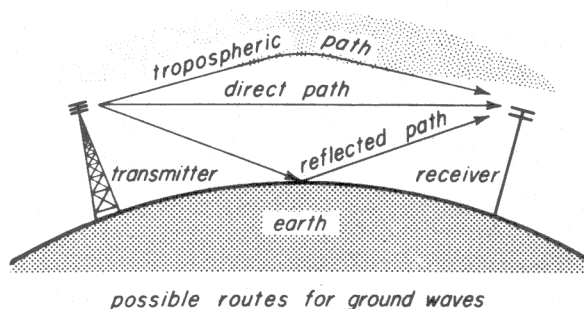
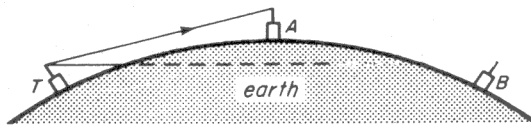


Fig. 32-3

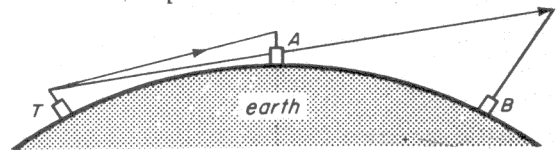


line-of-sight transmission -- low antennas

Fig. 32-4

antenna to the receiving antenna in a direct line if there are no obstructions along the way, and we speak of this as a *line-of-sight* characteristic. At low and medium-high frequencies the direct wave can bend around obstructions and still reach the receiving antenna. At very-high frequencies, any obstruction in the path of the direct wave deflects or absorbs too much energy from it and makes satisfactory reception impossible. Transmission by means of the direct wave can be extended by raising the transmitting or the receiving antenna, or both. This can be better understood by referring to Fig. 32-4. *T* is the transmitting antenna, while *A* and *B* are receiving antennas. Direct radio waves from *T* can be received at *A*, but not

at *B*. The distance between *T* and *A* is line of sight, but from *T* to *B* the curvature of the earth prevents a line-of-sight reception. Now let us increase the height of the antenna at *B* as shown in Fig. 32-5. Notice that the path between *T* and *B* is now line-of-sight, and reception by the direct wave is possible. A small distance can be added to the maximum line-of-sight distance, if we take into consideration a slight amount of bending around the curvature of the earth due to certain atmospheric conditions.



line-of-sight transmission -- height of "B" increased

Fig. 32-5

A convenient way of finding the maximum line-of-sight distance, if we know the antenna height, is by using the nomograph shown in Fig. 32-6. All you do is lay a ruler

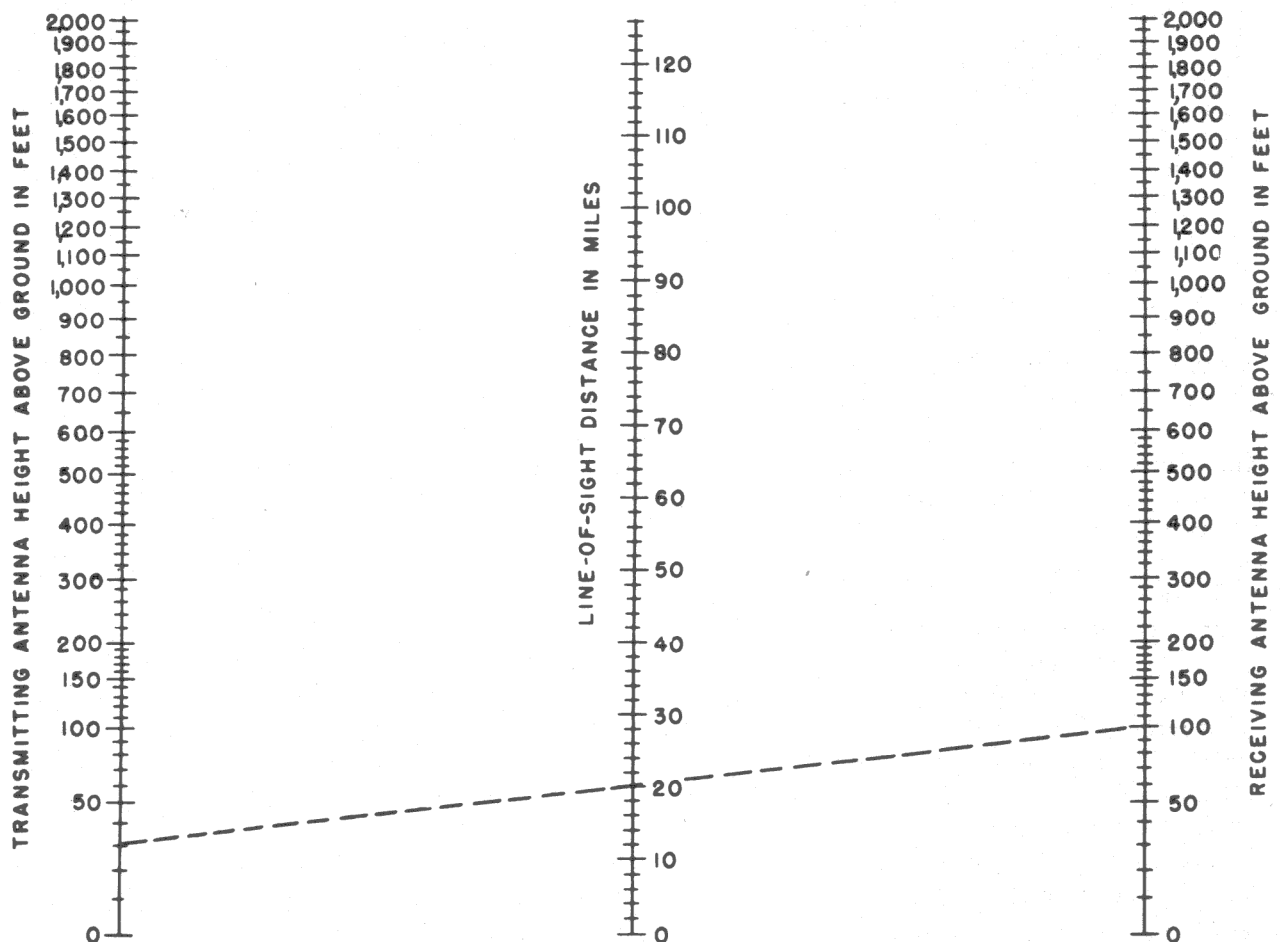


Fig. 32-6

on the chart so that you connect the height of the transmitting antenna with that of the receiving antenna. The maximum line-of-sight distance is read at the point where the ruler crosses the center line. As an example, suppose the antennas are 30 and 100 feet in height. By connecting these two heights on the chart by means of a ruler, we find that the maximum line-of-sight distance is 20 miles (see the dotted line on the chart).

Ground-Reflected Component. The ground-reflected wave is the part of the ground wave that reaches the receiving antenna after being reflected from the ground. Figure 32-7 shows two of the components of the ground wave — the direct component, which we have already discussed, and the ground-reflected component. The ground-reflected component strikes the earth at point Y in the illustration, and is reflected back by the earth.

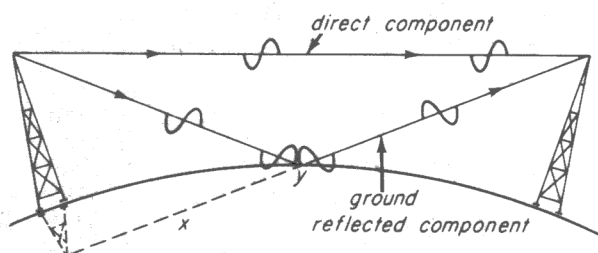


Fig. 32-7

As shown in Fig. 32-7, the ground wave might very well be coming from an imaginary antenna below the surface of the earth. This antenna is upside down and puts out a component that is 180 degrees out of phase with the direct component. Thus, it is just as if the actual antenna itself and the signal put out by the actual antenna are reflected in a mirror. At point Y, phase displacement of 180° takes place. As a result, the ground reflected component and the direct component are out of phase when they reach the receiving antenna. Actually, the phase displacement at the receiving antenna is somewhat greater than 180 degrees; the ground-reflected component arrives a little later than the direct component because it has to travel farther, as shown in the figure. If the distances travelled by the direct component and the ground-reflected component were the same, the waves would arrive at the receiving antenna 180 degrees out of phase and

cancel each other. This would result in no reception. However, there is always a difference between the distance travelled by the direct wave and that of the ground-reflected wave. This difference in distance causes a time lag between the two components, and this produces additional phase displacement. If the difference between the distance is equal to half a wavelength, the additional phase shift is 180 degrees, so that the total phase shift is 360 degrees. Under this condition, the two waves meet at the receiving antenna in phase, and their field intensities add to produce a stronger signal. The difference in distance travelled by the two waves can be increased by making the antenna heights greater. At low frequencies, one wavelength is comparatively large, and the increase in antenna heights will not produce too great an effect on the time lag. As the frequencies become higher, the wavelengths become smaller, and it becomes possible for the antenna height to be a wavelength or more above the earth's surface. When this is true, the distance travelled by the ground-reflected wave may be more than a half wavelength greater than that travelled by the direct wave, and this time lag will tend to bring the two waves more nearly in phase, so that the signal will be reinforced instead of cancelled.

Surface Component. The *surface* component follows the curvature of the earth. This component is most useful when the transmitting and receiving antennas are so close to the ground that the direct and ground-reflected wave components cancel each other. The distance that the surface wave can travel is dependent upon the conductivity of the surface over which it travels. The best type of surface for surface-wave transmission is water. In general, wet soil is better than dry ground. If communication depends to a great extent upon the surface wave, it should be transmitted as a vertically polarized wave, owing to the fact that horizontally-polarized waves tend to become short-circuited by the earth or the surface over which the waves travel.

Tropospheric Component. The *tropospheric* component of the ground wave is refracted or bent in the troposphere. Be-

cause these changes depend on weather conditions, refractions from the troposphere vary, and can cause fading or variations in field intensity. Although the tropospheric wave is unreliable, tropospheric refraction makes broadcasting possible over distances far greater than can be covered by the other ground-wave components.

How the Ground Wave is Used. The ground-wave components provide possibilities for communication over short and moderate distances. The surface component is the most useful of all the ground-wave components when the surface has high conductivity; otherwise, the direct wave combined with the ground-reflected wave produces the best reception. The low-frequency band (30 kc to 300 kc) is transmitted for moderate distances by means of ground-wave communication. For these frequencies, the direct and ground-reflected components are not useful, because of the cancellation of the signals as a result of the 180-degree phase shift. The surface wave carries the information; the ground losses of the vertically-polarized wave is small, and the wave can follow the curvature of the earth for several hundred miles. The medium-frequency band (300 kc to 3,000 kc) is sent for moderate distances over land and for fairly long distance communication over sea water by means of ground-wave transmission. Close to the upper end of this band, the surface component tends to decrease in field intensity more than for the lower frequencies of the same band. Therefore, the higher frequencies of this band cannot be propagated for as great distances as the lower frequencies. The high-frequency band (3,000 to 30,000 kc) is transmitted by means of ground waves. The band of very high frequencies (30,000 kc to 300,000 kc) is transmitted by line-of-sight transmission—chiefly by means of the direct component. The range of the direct wave can be extended by increasing the heights of the antennas.

32-3. SKY WAVES

When radio signals were successfully transmitted across the Atlantic Ocean, there was no satisfactory explanation of how such long-distance transmission was possible.

Then two scientists, Heaviside and Kennelly asserted that the earth is surrounded by an electrified layer that reflected radio waves back to the earth. Later, it was learned that there are several layers of gases, that these gases are ionized, and that these ionized layers act as reflectors that tend to prevent the escaping of radio waves into free space and bend them back towards the earth. The name given to all these layers is *ionosphere*. There are actually four layers of the ionosphere called the *D*, *E*, *F₁*, and *F₂*. However, all four layers exist simultaneously only in the daytime, in that portion of the atmosphere exposed to the sun. At night, the *F₁* and *F₂* layers combine to form a single *F* layer, and the *D* and *E* layers fade out. The heights of these layers, and the intensity of the activity of the gases vary from hour to hour and from day to day. The *D* layer is the lowest, and lies between 30 and 55 miles above the earth's surface. This layer has little effect in bending the paths of high-frequency radio waves, it weakens them as they cross this layer on the way to the higher layers. Another effect of the *D* layer is to cause complete absorption of low and medium-frequency waves. Due to the fact that the *D* layer is present only in the daytime, the field intensity of high-frequency waves that are reflected by the ionosphere is lower in the daytime than at night.

The *E* layer lies between 55 and 90 miles above the earth's surface. The layer's height varies with seasons, and the effect of the layer on the reflections of radio waves varies with the time of day. The *E* layer reaches its most effective point at about noon, and then decreases gradually so that at night it is practically useless for high-frequency communication. This layer can be used for daytime transmission of radio waves at frequencies as high as 20 mc, and for distances up to 1,500 miles.

At heights between 90 and 240 miles are the *F₁* and *F₂* layers. They are effective at all hours of the day or night. Although they are two separate layers in the daytime, they merge into one layer at night. At night the height of the layer is at a height of about 170 miles. The *F₂* layer is the most useful of all layers for long distance communication.

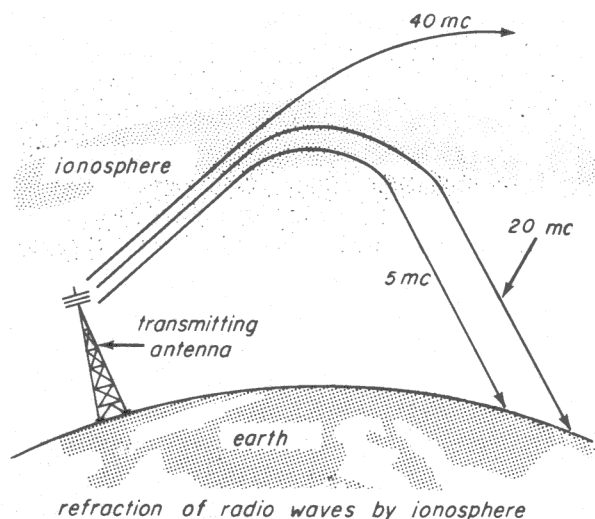


Fig. 32-8

Sky waves travel in straight lines until they reach the ionosphere. Since the ionosphere is of a different density than the lower atmosphere, a radio wave that enters it is bent. The amount of bending is determined by the frequency of the wave and the angle at which it enters the layer, as shown in Fig. 32-8 and 9. Figure 32-8 illustrates three separate waves, of different frequencies, entering the ionosphere at the same angle. The 5-mc and 20-mc waves are refracted enough to be returned to the earth, but the 40-mc wave is not refracted enough and goes right through the ionosphere. Notice that the 5-mc wave is refracted more than the 20-mc wave. For a given angle, there is a frequency above which the waves will not be returned to earth by the layer. This is called the *critical frequency* for this angle.

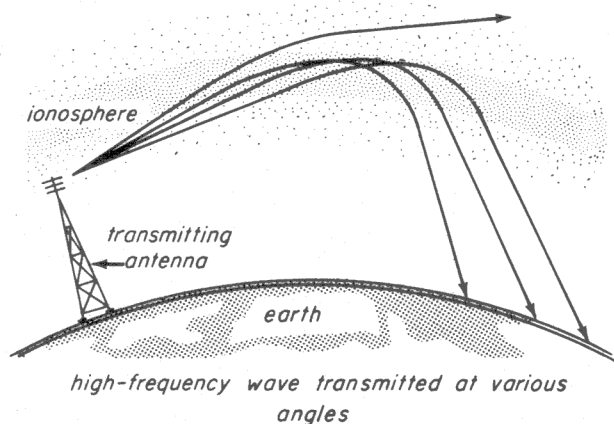


Fig. 32-9

Figure 32-9 illustrates how a wave of a given frequency would be affected if it reached the ionosphere at one or another of four angles. The *critical angle* is the greatest angle at which the waves of that frequency will be returned to earth. All waves that enter the ionosphere at angles above the critical angle will *not* be returned to earth, and all waves that enter at angles lower than the critical angle will be bent enough to be returned to earth.

Sometimes one layer of the ionosphere will bend a wave, but not enough to cause it to return to the earth. As the wave continues upward, it may be bent more by another layer of the ionosphere. Waves that are not returned by the *E* layer may be bent enough by the *F* layers to return to earth. In Fig. 32-10, waves between 15 and 30 mc are bent slightly by the two lower layers, but not enough to return to earth. However, these waves reach the highest layer, *F*₂, and then they are bent enough to be sent back to earth.

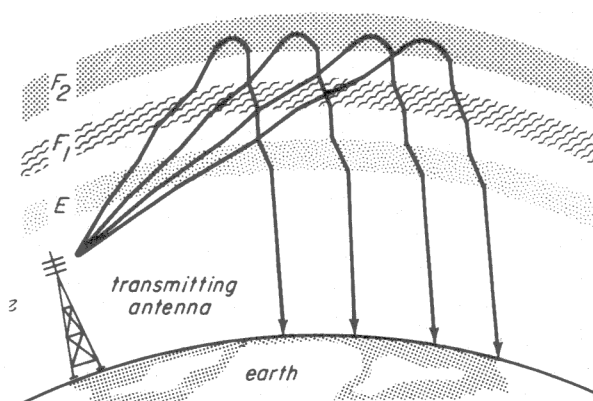


Fig. 32-10

Notice in Fig. 32-8 and 9 that the sky waves return to earth at various distances from the transmitter. Sometimes the sky wave returns to earth so close to the transmitter that it meets the ground wave. When this happens, the sky and ground waves interfere with each other and cause fading because their phase relation constantly shifts from in-phase to out-of-phase, (when in-phase they add, when out-of-phase, they cancel).

Most frequently, the sky waves return to earth beyond the range of the ground waves.

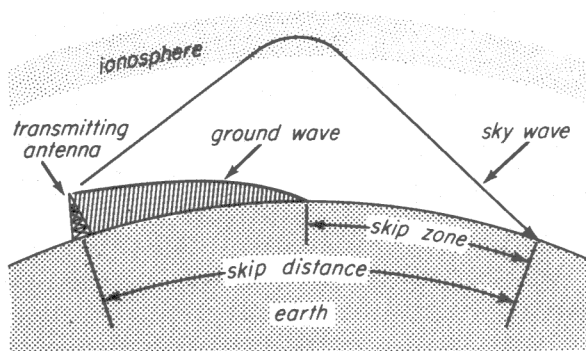


Fig. 32-11

The distance between the transmitter and the closest sky wave returned to earth is called the *skip distance* (See Fig. 32-11). The ground wave fills some of the skip distance. However, there is a gap between the point where the ground wave ends and the closest sky wave strikes the earth. This gap is called the *skip zone*. In this gap, no signals are received from the transmitter shown. Sometimes, there is no skip zone; in such cases, the skip distance is less than the ground-wave range.

Communication by means of sky waves is subject to many variable conditions, and therefore it is necessary to determine in advance whether certain frequencies can be used at various times of the day and various seasons of the year. At any particular time, there is a certain lowest useful high frequency and a highest useful high frequency. There is also a certain frequency recommended as the best high frequency to use at a given time. This is usually about 15 percent below the highest useful frequency, the 15-percent margin serves to make up for any day-to-day changes in the highest useful frequency, for the month. The United States Department of Commerce publishes monthly graphs and charts about the uses of various frequencies in sky-wave propagation.

We have seen that there are quite a number of factors involved in the travel of radio waves from transmitter to receiving antenna. In order for the receiver to pick up the radio signals, they must reach the antenna with sufficient field intensity to overcome the effects of fading and noise. Fading may be due to a number of things. It may be caused by two or more out-of-phase waves from the same source reaching the receiving

antenna. These waves will sometimes interfere with each other, and sometimes reinforce each other, causing changes in received signal strength. Fading may also be caused by changes in polarization of the signal. Changes in polarization sometimes take place in the radio waves as they travel downward from the ionosphere. A receiving antenna, set up to receive signals with a particular polarization will not receive signals with a different polarity as well as those with the same polarity. Some radio waves fade because of the amounts of energy lost in the ionosphere by absorption. When a radio receiver is near the limit of the skip distance, signals may fade when changes in the ionosphere cause the skip distance to change, thus placing the radio receiver in the skip zone.

In addition to fading, there are other possible difficulties that prevent good reception of sky waves. Among these difficulties is noise. Noise in a radio receiver may be man-made, such as noise caused by the ignition systems of automobiles, or electrical equipment in the home, or noise may be caused by atmospheric conditions such as thunderstorms, rain, snow, or duststorms. Another type of noise, called receiving-set noise, is caused by the random motion of electrons in vacuum tubes and other circuit components.

Normally, sky-wave communication is not considered useful for the broadcast band, although *unusual* reception in this band can only be accounted for by means of sky waves. Frequencies from 1 to 3 mc are transmitted by sky-wave transmission at short distances during the night. Frequencies from 4 to 8 mc are transmitted for short distances during the day and for long distances at night. Effective long-distance sky-wave communication during the day uses a range of 8 to about 25 mc. Above 12 mc, the skip distance at night becomes very large, and the sky wave is normally not bent back to earth. Thus, 16 mc is an excellent daytime frequency for long-distance sky-wave transmission, but it is not usable at night. These are average frequencies for average conditions over a long period of time, and should not be understood as being exact at all times.

32-4. GENERALIZED ANTENNA THEORY

The design features that make an antenna a good radiator also make it a good receiving antenna. For this reason antennas often are discussed as though they were planned for transmission rather than reception of signals. However, since the behavior of antennas is reciprocal — that is, an antenna used as a receiving antenna behaves electrically much as it does when used as a transmitting antenna. This should not cause confusion. So, when we discuss antennas, we sometimes find it useful to think of the antenna as a transmitting antenna with an r-f generator connected at the center or at the end of the antenna. Then we can theoretically derive the behavior of the antenna.

In order to be as efficient as possible, an antenna must have a length that is in a certain proportion to the length of the wave it is intended to radiate or receive. Antennas are named accordingly. Thus, a *quarter-wave* antenna is one whose length is one-quarter as long as the wavelength it is designed to receive; a *half-wave* antenna is one whose length is half a wavelength long, and so on.

Wavelength is not exactly the same numerically in antennas as it is in space, because the speed of an electromagnetic wave along a copper wire is not quite as great as the speed of the same wave in space. Therefore, the wavelength of a 10-mc signal is 30 meters in space; it might be only 28.5 meters in a certain kind of copper wire. Therefore, although a copper wire of this type that is only 28.5 meters long would not be one wavelength long physically, in terms of wavelength in space, but it would be one wavelength long *electrically* (in terms of wavelength in the wire itself). A quarter-wave antenna made of this wire would not be 7.5 meters long, but 7.125 meters long. A quarter-wave antenna is a quarter wave long electrically; a half-wave antenna is a half wave long electrically, and so on. For frequencies up to 30 mc, the electrical length is about 95 percent of the free space length, if the length is much greater than the diameter of the wire used. However, above 30 mc, the type of wire used makes some difference in the electrical length of the antenna. To convert meters to feet, multiply meters by 3.28.

To determine the physical length in feet of a quarter-wave, the following formula can be used:

$$\text{length (in feet)} = \frac{234}{\text{frequency in mc}}$$

Often times, a quarter-wave antenna is grounded, generally through a coupling coil. Such an antenna is called a Marconi antenna.

The physical length of a half-wave antenna in feet can be found by the formula:

$$\text{length (in feet)} = \frac{468}{\text{frequency in mc}}$$

A half-wave antenna is generally *not* grounded and may be called a Hertz antenna.

Half-Wave Antenna. The basic unit in antenna design is the half-wave antenna and may be horizontally or vertically polarized. It is the shortest possible resonant antenna. An antenna is the proper length to be resonant at a fundamental frequency if an r-f current at that frequency fed to one end of the antenna can travel *to the far end of the antenna and back* in precisely the time of one r-f cycle. (At the far end of the antenna, the current may be considered to be reflected back, as light is reflected by a mirror.)

Standing Waves. When the energy of the resonant frequency applied to a half-wave antenna reaches the far end, it stops because there is no place farther that it may go. This causes a collapse of the magnetic field, which establishes an electrical field that adds to the existing charge. This charge causes a current flow back toward the generator until the charge reaches the generator-end of the antenna just as the generator is starting the next charge along the wire. The two charges aid each other and start current flowing away from the generator end and down toward the free end of the antenna. At each end of the antenna, the charge (voltage) is high while the current is minimum.

If a generator is feeding a cycle of r.f. at the fundamental frequency into the half-

wave antenna, any energy left from the preceding cycle will be starting on its second trip to the far end just as a new cycle of current starts into the antenna from the generator. The new surge of current, and the reflected surge will travel in phase along the wire. The antenna will act like a resonant LC circuit and absorb energy from the generator. The losses will be made up by the generator. The principal loss will be due to radiation of energy into space.

For a half-wave antenna, the distribution of current and voltage are as shown in Fig. 32-12 at *a* and *b*. Conditions during one half of a cycle are shown at *a*. Current is zero at the ends and maximum at the center. Voltage is maximum at the ends and zero at the center. During the next half cycle, shown at *b*, current is flowing in the opposite direction. It is again zero at the ends and maximum at the center. Voltage polarity is reversed, but voltage is again maximum at the ends and zero at the center. Actually, due to resistance and other factors, voltage is *near zero* but not quite zero at the center. Similarly, current is *near zero* at the ends. If a perfect, resistanceless antenna could be constructed, voltage and current would be zero at the points indicated. Since the *location* of current and voltage maximums and minimums do not vary from cycle to cycle, they seem to be a wave fixed in position. Such a wave is called a *standing wave*.

Note that the standing wave of voltage on a half-wave antenna is zero at the center. At the two extreme ends of the antenna, the voltages are equal amplitude and opposite polarity. The electric or electrostatic lines will appear across the two points. At corresponding distances away from the center, lower values of standing wave of voltage will appear, and corresponding electric lines will appear, as shown in Fig. 32-12*c* which shows the state of electric lines for the standing wave voltage shown at *a*. It would appear that the half-wave antenna has capacitance, since a capacitor stores energy in the form of electric lines. An electric field exists between the ends of the antenna. When current is flowing an electromagnetic field exists around the wire. Since the standing wave current is maximum at the

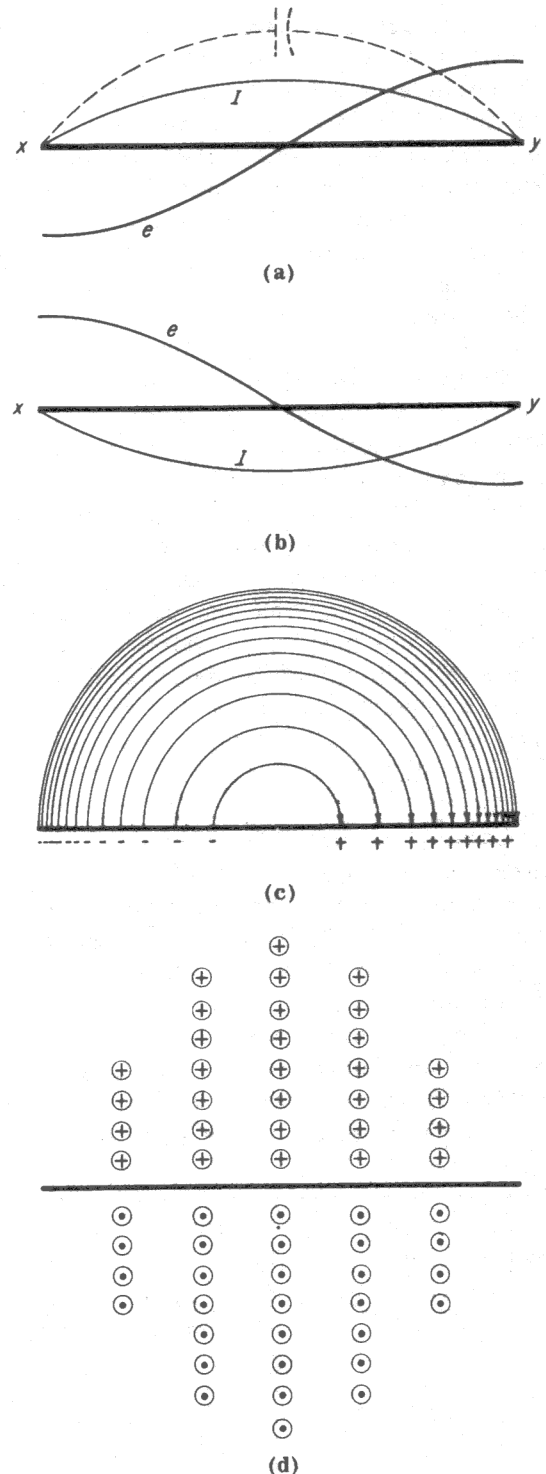


Fig. 32-12

center and minimum at the ends of a half-wave antenna, there will be an electromagnetic field about the antenna. The field is greatest at the center and decreases away from the center. This is shown in Fig. 32-12*d*, which indicates the condition for the standing wave of current shown in Fig. 32-12*a*. The antenna also appears to have in-

ductance, since an inductor has an electromagnetic field. Thus the space around the antenna is pulsating with energy. Since the natural resonant period of the antenna is the same as the period of the exciting signal from the generator, the antenna can absorb much energy from the source and put it into the fields. Such an antenna is well coupled to the space surrounding it, and will radiate effectively.

Radiation Resistance. Transmitting antennas are said to have radiation resistance. This simply means that, since the antenna is a load on the transmitter, it absorbs a certain amount of power from the transmitter, and is therefore equivalent to whatever resistor would have to be connected in place of the antenna to draw the same amount of power. If, for example, a resistor of 60-ohms, connected in place of the antenna, draws the same amount of power as the antenna, the antenna is said to have a radiation resistance of 60-ohms.

Center-Fed Half-Wave Antenna. A half-wave antenna does not have to be supplied at the end. It may be cut and fed at the center (Fig. 32-13), if the source from which it gets its signal has the same impedance as the antenna has at its center. Since, in a resonating half-wave antenna the standing wave of current is normally high at the center and standing wave of voltage is low, the impedance equal to the ratio of voltage

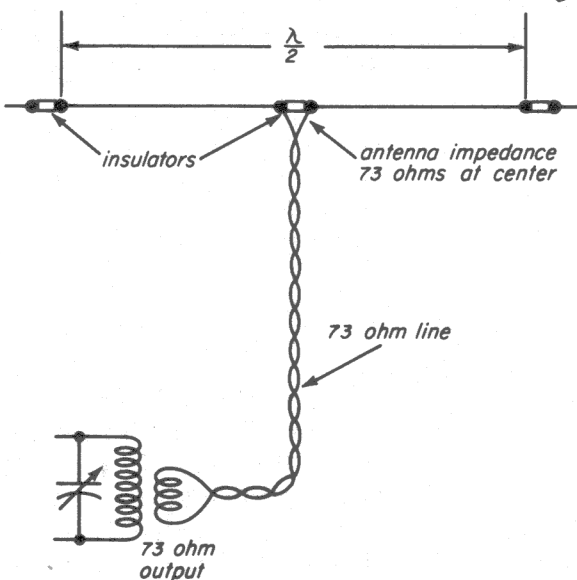


Fig. 32-13

divided by current must be low at the center. Experiment and theory show that the impedance is about 73-ohms. If a transmitter has an output impedance of 73-ohms, and is connected to the antenna by a transmission line whose natural or characteristic impedance is also 73-ohms, a good match exists, and power is efficiently transferred to the antenna. The r-f energy is radiated.

A half-wave antenna may be run horizontally, as in the figure, or vertically. When mounted vertically, it will radiate uniformly in all the geographical directions (north, east, south, west), but when mounted horizontally, it will be directional, radiating little or no energy in the direction it points, and much of its energy in a direction broad-side (at right angles) to the antenna.

Vertical Half-Wave Antenna. If we could raise a vertical half-wave antenna high above the earth, so that ground reflections would have little effect upon its fields, we would find that the strength and direction of its free-space radiation could be represented by the diagram of Fig. 32-14. It shows the half-wave antenna surrounded by a form that resembles a fat doughnut. This is a solid graph. It shows the *proportions* of the total energy radiated in the various directions. So that the graph can be more clearly interpreted, let's cut the doughnut in half from top to bottom, cutting through

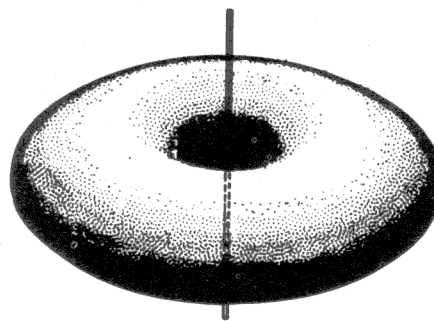


Fig. 32-14

the entire length of the antenna at the same time (Fig. 32-15). Let's suppose that this antenna is being used to radiate energy to three receivers. The length of arrow X represents the strength of the radiation, in the direction of a receiver located at point P. The length of arrow Y represents the strength of the radiation in the direction of a receiver

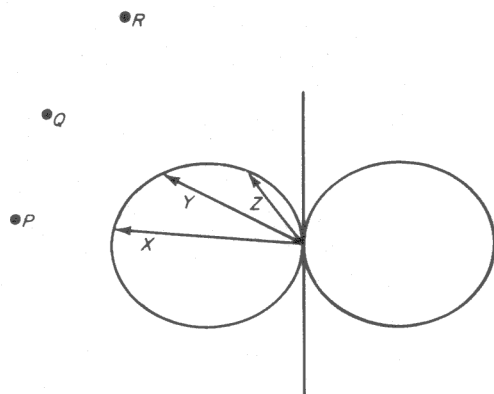


Fig. 32-15

at point Q . The length of arrow Z represents the strength of radiation in the direction of R . In each case the direction is taken from the center of the antenna. The length of the arrows shows that the radiation leaving the antenna at right angles is strongest; in another direction, Y , the amount of energy radiated is only about 0.8 as much as the broadside radiation; in still another direction, Z , the amount of radiated energy is only about 0.4 as much as the broadside radiation.

Notice that the tips of the arrows just reach the nearly circular lobe, as the curved outline is called. If we wanted to find the relative strength of radiation in some direction not shown by any of the three arrows, we would simply draw a line, from the center of the antenna, in the direction desired. Where the line intersected the lobe, we would draw the arrowhead. We would immediately see how radiation in that particular direction compared to radiation in the broadside direction. The lobes are simply the lines connecting all possible arrowpoints, or vector ends, that describe the relative field strength in all directions.

If the antenna were connected to a receiver, and if points P , Q , and R were three different locations of an aircraft transmitter operating at the frequency for which the antenna is a half-wave long, then the arrows would indicate how the received signal grew stronger as the plane changed altitude and moved from R to Q to P , even though all three points are equally distant from the center of the antenna.

These field-strength relationships would hold true for either side of the antenna, as shown by the fact that the lobes are equal in size and shape. The lobes describe the radiation pattern of the antenna, which is said to have a figure-of-eight pattern because of their resemblance to that numeral.

Notice that an arrow drawn from the antenna's center along the antenna's length would be outside the lobes. This means that there would be no radiation and no pickup whatever, in that direction, in an absolutely perfect half-wave antenna. Practical antennas are not quite perfect, so a very small percentage of radiation or pickup would exist in that direction.

Horizontal Half-Wave Antenna. If the horizontal half-wave antenna is at a great height (many wavelengths) above the earth so that it is essentially in free space, it has the radiation pattern described for the free-space vertical antenna, except that, since the antenna is horizontal, the axis of the doughnut is also horizontal.

If the antenna is extended in a north-south orientation, its broadside radiation will be strongest in east-west directions, and weakest in north-south directions. As stated before, the horizontal half-wave antenna is directional, with respect to the ordinary compass directions. (The vertical half-wave antenna is directional with respect to up or down, but not with respect to directions along the earth's surface, since any compass direction is broadside to it.)

Since ground is broadside to a horizontal antenna, considerable energy from the antenna strikes the ground and is reflected back up toward the sky. Energy leaving the antenna and travelling straight down is reflected back up along its arrival path. Energy radiated to ground at any angle other than perpendicular will be reflected skywards at some angle other than perpendicular. Depending on the height of the antenna and the direction of reflection, it may leave the area of the transmitter in phase with directly radiated energy from the antenna. In this case, the reflected energy will reinforce the direct radiation. But at

some other angle of departure, it may be out of phase with the direct radiation, and greatly weaken it, by cancellation. Since the sky wave is very important in long-range communication, the height of the antenna should be chosen so that the reflected wave will leave the transmitter area in phase with the direct wave, at the sky-wave angle most frequently employed.

The energy reflected upward perpendicularly sees the antenna as a receiving antenna, and induces a strong current in it at the resonant frequency. Depending upon the height of the antenna, the reflected wave will arrive at a time that induces a current either in phase or out of phase with the original current. When it is in phase, more current flows in the antenna. When it is out of phase, less current flows in the antenna. More current flowing in a load (antenna) for the same power input to the load is equivalent to a decrease in load impedance. Less current is equivalent to an increase in load impedance. Therefore, the radiation resistance of the antenna varies with height.

Grounded Quarter-Wave Antenna. If the lower end of a vertical quarter-wave antenna is directly grounded, the antenna behaves like an ungrounded half-wave antenna. Such an antenna is called a **Marconi antenna**. This happens because ground reflections reinforce the fields of the quarter-wave section in the same way that the missing quarter-wave section would. In fact, such a quarter-wave antenna may be considered as a half-wave antenna driven half way into the ground, since the ground is the equivalent of the missing section (Fig. 32-16a). The resonant frequency is that of a half-wave antenna.

If the vertical quarter-wave section is made appreciably shorter than that required by the desired resonant frequency, a coil can be inserted between the lower end of the antenna and ground. The coil has the effect of increasing the electrical length of the antenna, bringing it back to resonance if the coil has the correct inductance (Fig. 32-16b). A signal can be introduced into the antenna, or taken off when picked up by the antenna, if suitable tank circuits are coupled to the coil.

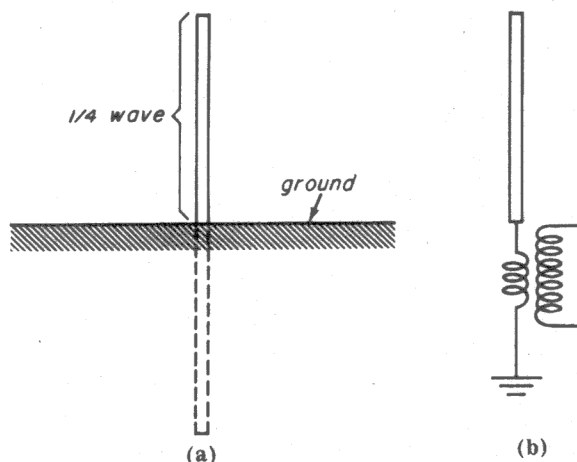
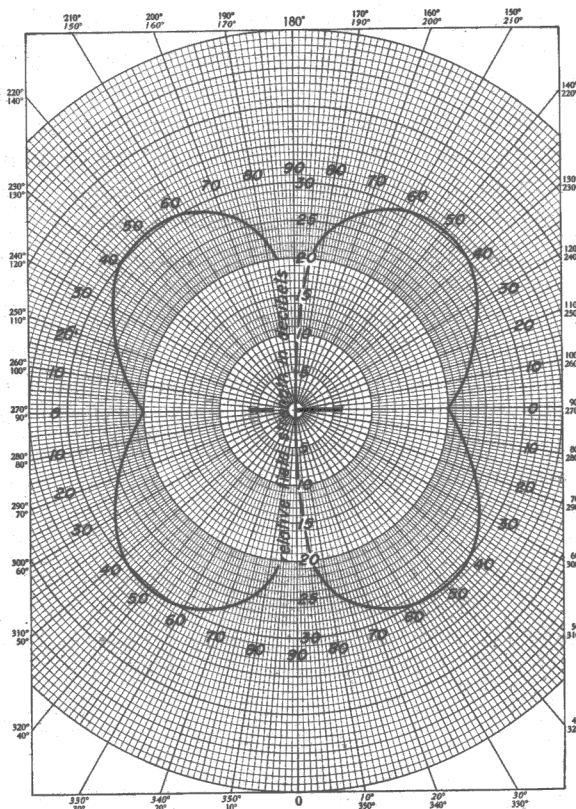


Fig. 32-16

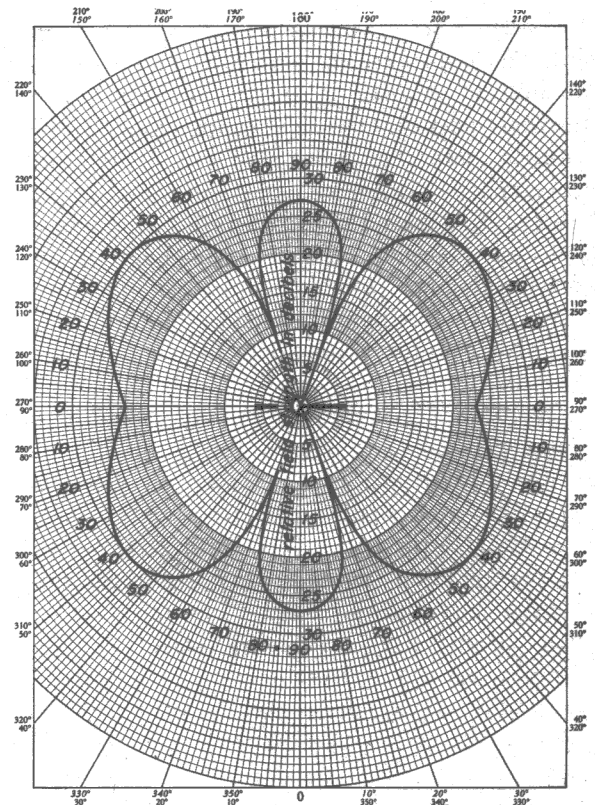
Multiples Of Half-Wave Antennas. Antennas with lengths that are multiples of a half-wave such as the full-wave antenna, the $3/2$ -wave antenna, the two-wave antenna, etc., are resonant at harmonics of the fundamental frequency to which the half-wave antenna is resonant. Furthermore, if an antenna is a half-wave antenna, for a frequency of 10 mc, it will be a full-wave antenna for a frequency of 20 mc, a $3/2$ -wave antenna for 30 mc. When used at these multiples, it is called a long-wire, or harmonic antenna. Its radiation pattern changes for each multiple. Figure 32-17 at *a* shows its pattern when used as a full-wave antenna. At *b* is its pattern when used as a $3/2$ -wave antenna. Note that it has more lobes as a harmonic antenna. The small lobes in *b* are called minor lobes. Note also the kind of graph paper on which the lobe-pattern is drawn. It is called *polar coordinate* graph paper, used to plot related intensities and directions. Intensities are indicated by distance from the origin, or center. Directions are self-evident.

32-5. A-M BROADCAST-BAND RECEIVING ANTENNAS

For adequate signal pickup, the antenna length should be at least a quarter-wave. That means an antenna cut for the middle of the AM broadcast band (1 mc) would be 234 feet. For the average home-type installation, the required length presents a problem. However, a shorter antenna can be used. Since the signal sent out by broadcast stations is extremely strong, it is not difficult to design an antenna to pick it up. Therefore, it



(a)



(b)

Fig. 32-17

is not necessary to apply strict antenna theory when dealing with AM broadcast band receivers. Let's discuss the two types of broadcast band antennas — outdoor antennas and indoor antennas.

Outdoor Antennas. The simplest type of outdoor antenna is a solid or stranded insulated copper wire, mounted vertically, that goes up in the air to a height between 20 and 50 feet. This wire is connected at its lower end to a coil, and the coil is connected to ground. Radio energy propagated from the broadcast station strikes this wire and induces a voltage in it and the coil to which it is connected. The coil is coupled to the first stage of a radio receiver; the voltage in the antenna coil induces signal voltage that is fed to the control grid of the first stage.

At broadcast frequencies, a good general rule is that the longer the antenna, the more signal it will pick up. Furthermore, the higher above the ground an antenna is, the less likely it is that it will pick up unwanted noise from electrical appliances and other man-made noise emitters. Therefore, it is

useful to have the main portion of the antenna on a rooftop or some other high place. A lightning arrester should be installed, outside the house, in the lead-in going to the receiver.

An antenna need not be a straight wire. A very common type used with broadcast sets is the inverted-L or Marconi antenna, shown in Fig. 32-18. Just as in the case of

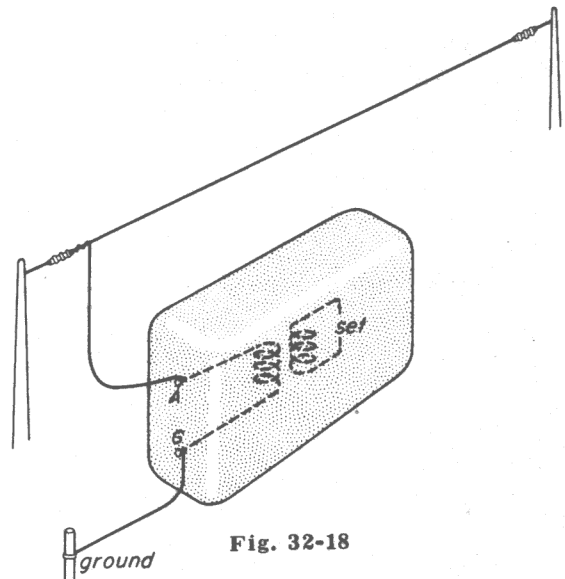


Fig. 32-18

the simple straight wire antenna, increasing the length of the antenna will increase the amount of signal it picks up. Either the vertical part or the horizontal part of the antenna can be made longer. It is more practicable to make the horizontal part longer. You should get satisfactory results from an antenna of this type even if the horizontal part is only 60 to 75 feet long, although a horizontal portion 50 feet long will still provide good results.

In order to avoid noise, it is wise to mount the antenna above the ground, such as on a rooftop, as far away as possible from any electrical lines that could interfere with radio reception. Both ends of the flat-top portion should be supported with antenna insulators of porcelain, glass or other high-grade insulating material. The purpose of these insulators is to prevent part of the signals from leaking off to ground through the masts that support the antenna, especially in rainy weather. The insulators should be connected to the masts with five to ten feet of strong wire. Figure 32-19 gives the details of connecting the insulator between the antenna and its supporting post.

The lead-in (which should be insulated) should be kept away from any source of electrical noise interference. The electromagnetic waves of such interference are usually vertically polarized, so the lead-in, which is usually vertical, tends to pick up such noise waves. In noisy localities, the lead-in should be as short as possible. Where a long lead-in is required, the flat-top should be made long enough to provide a high signal-to-noise ratio. This is discussed in Service Practices 5, which also gives instructions erecting antennas and running lead-ins.

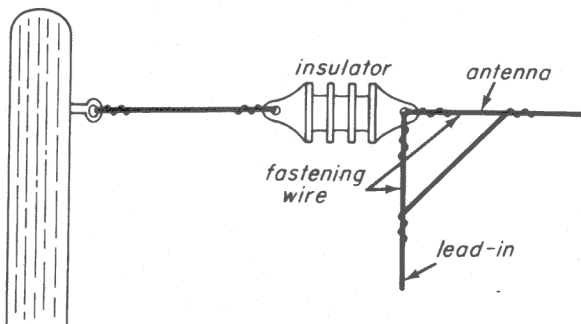


Fig. 32-19

Once the lead-in has been brought into the building, it should be strung along walls, baseboards, or mouldings in the straightest possible line until it reaches the receiver. To complete the antenna circuit, the ground terminal of the receiver should be connected through insulated copper wire to a water pipe, steam radiator, or to a ground rod in the earth. The connection between the ground wire and the water pipe should be made with a ground clamp, especially made for this purpose, because a wire that is merely wrapped around the pipe will not make a good ground connection. A good ground connection is an important part of the Marconi antenna and should never be omitted.

Where the pickup of nearby electrical noise (man-made static) is a problem, it is sometimes possible to reduce the noise pickup by means of a shielded lead-in (Fig. 32-20). The grounded shield prevents pickup of noise by the lead-in.

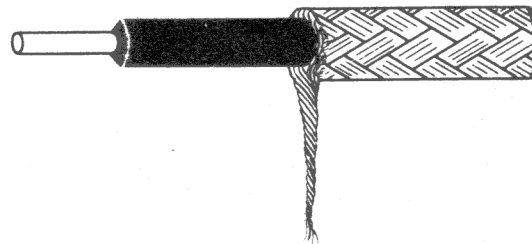


Fig. 32-20

Indoor Receiving Antennas. The simplest type of indoor antenna consists of a length of from six to twenty feet of wire. This wire has one end attached to the antenna terminal of a broadcast receiver, and the other end strung out behind the set in a straight line, thrown under a rug, or laid along the moulding of the room. The wire should be insulated. Such an antenna will not deliver as strong a signal to the receiver as an outdoor antenna of the same size, but a receiver with high gain will boost the signal to sufficient strength. If the receiver has one r-f stage and two a-f stages, an indoor antenna can often bring in satisfactory signals from stations that are hundreds of miles away.

Loop Antennas. The type of antenna most often used in home-type and portable broadcast receivers is the loop antenna. It is

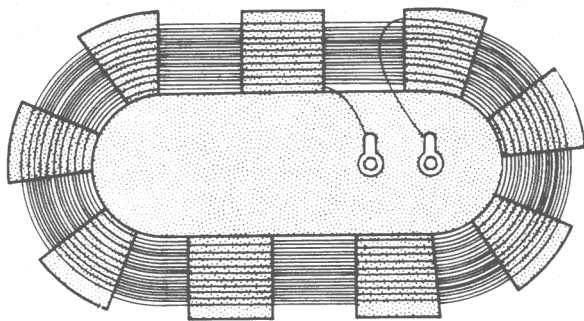


Fig. 32-21

built into the set so that no wire protrudes outside the cabinet, and can be better than the simple indoor antenna just described. It usually is in the form of a flat coil of wire wound in a plane around a cardboard or fiberboard form that serves as the back of the radio set (Fig. 32-21). Loop antennas are also made by means of stamping or etching the coil onto a fiberboard form (Fig. 32-22). A stamped or etched antenna has the advantages of lower cost and smaller space requirements. The loop antenna does not receive well in all directions. Best results are obtained when the set is turned so that the plane of the loop is parallel to the direction from which the radio signal is coming. The received signal is weakest when the plane of the loop is at right angles to the direction from which the signal is coming. If a weak station is tuned in, reception can usually be improved by turning the set until the signal is loudest.

The loop antenna is connected in the receiver's circuit in place of the secondary winding of an antenna transformer. There is no antenna transformer primary. The loop may be regarded as an enlarged secondary,

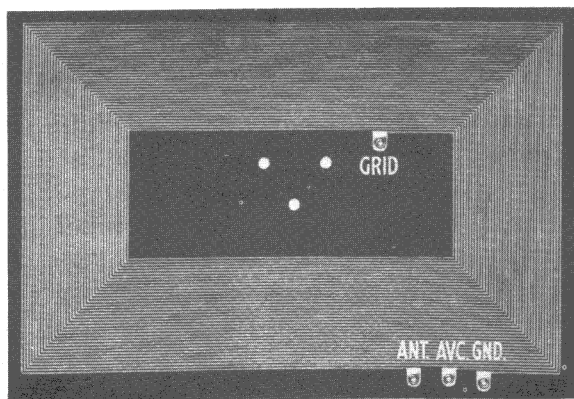


Fig. 32-22

made big enough to have good capture area. When the secondary is big enough to have adequate pickup of local stations all by itself, the outside antenna and the primary winding are not needed. If the secondary is wound in a flat plane, it uses up little space in the receiver cabinet, yet it retains its capture area. The larger the loop, the more signal it can intercept. The size of the cabinet, however, puts a practical limit on the size of the loop chosen.

Care should be taken to mount the loop antenna as far away from the chassis of the receiver as the room available in the cabinet permits. If the loop is pressed against the chassis, it is in a no-signal region. Its pickup will be greatly reduced. Therefore, when damaged loops are replaced, they should be located an inch or more away from the chassis.

In many receivers, no trimmer capacitor is found on the r-f section of the variable capacitor. In such cases, it will usually be found mounted on the cardboard or fiber loop form. It is connected in parallel with the r-f section of the variable capacitor by the wires which connect the loop to the variable capacitor. It should not be adjusted until the receiver is in the cabinet. Then it should be peaked on a weak station near the high end of the dial.

Occasionally, in broadcast receivers, a loop antenna will have very few turns. However, if the loop is large, the capture area is large. But because the loop has few turns, it does not have enough inductance to resonate with a standard variable capacitor and cover the broadcast band. In such a case, as shown in Fig. 32-23, loop L_1 is usually in series with a small, high-Q inductor, L_2 . The total inductance will be

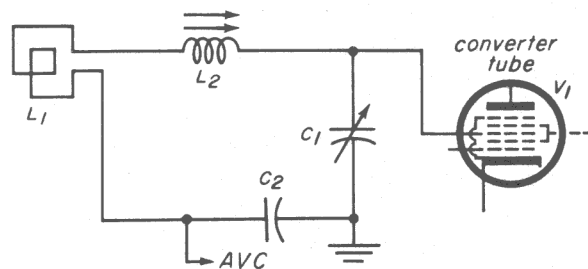


Fig. 32-23

just right for the broadcast band. Most of the total inductance will be in L_2 which can be given a high-Q very easily. Most of the capture area will be in the loop. This combination yields very good pickup of weak stations. Fairly thick wire may be used in the loop, making it mechanically strong, and giving it very little resistance.

If a receiver is located in a rural area, away from strong local stations, a loop antenna alone may not provide sufficient signal pickup. However, additional pickup can be provided by adding an external antenna to the loop. This is done by means of connecting the external antenna to a grounded coil and using the grounded coil as the primary of an r-f transformer and the loop antenna itself as the secondary of the r-f transformer. Many loop antennas have the primary loop already connected in place, wound around the secondary as shown in Fig. 32-22. In order to connect an external antenna to the installation shown, you would connect the external antenna to the terminal marked ANT, and run a ground wire to the terminal marked GND. (The AVC and GRID wires would already be connected to the receiver.) When such an antenna is used, a weak station should be tuned in. Then the receiver as a whole should be rotated to see if at some position the reception improves very noticeably. The reason for this test is that the loop continues to pick up signal independently, even when the outside antenna is also inducing a signal in it. If the set happens to be turned in the wrong direction, the independent pickup of the loop may be in such phase as to oppose the signal supplied by the outside antenna. By rotating the set, the phase of the loop's direct signal can be reversed. If this happens to put the receiver in a position which turns its front to a wall, the receiver may be restored to its normal position and the antenna and ground connections reversed.

Some loops have provision for an external antenna but no provision for a ground wire. In this case, the end of the primary that is intended for ground is already connected through a capacitor (about $0.01 \mu\text{f}$) to the chassis, which serves as ground.

When a loop has primary and secondary wound so close together that you cannot easily tell by visual inspection which winding is connected to which terminal lugs, you can quickly decide the matter with your multimeter. The two lugs that have the least d-c resistance between them are the low impedance primary. The secondary has many more turns and therefore more d-c resistance — 2-ohms, or so. (A very few loops in old receivers were exceptional. They had high impedance primaries, wound on a separate form attached to the loop form. The d-c resistance of these primaries, wound with many turns of fine wire, was as much as ten times the d-c resistance of the loop.)

Radiation Pattern Of The Loop Antenna.

The radiation pattern of the loop antenna is a doughnut (or figure-of-eight, if viewed in a single intersecting plane), like that of the half-wave antenna. But, unlike the half-wave antenna, the axis of the doughnut is not in the plane of the loop; instead it is perpendicular to the plane of the loop. If we pass a plane, perpendicular to the plane of the loop, through the center of the loop, we can see how the figure-of-eight pattern is related to the loop, as illustrated by the perspective drawing of Fig. 32-24a. Looking down upon the loop from above, the loop and the lobes (if the lobes were visible) would appear as at *b*. Note that the pattern is shown with the lobes equal in size and shape. This condition exists only when the loop is connected to a receiver in the way that is used for direction-finding equipment. For such a connection, shown at *c*, the two ends of the loop are balanced with respect to ground, by adjusting the compensating capacitors C_1 and C_2 . The center of the loop is grounded. This arrangement insures that equal voltages alike in polarity, with respect to ground, will develop across the halves of the loop, and will appear at the terminals of the loop when a signal arrives at the loop from the broadside direction. No voltage difference will exist between the terminals; there will be no signal. When the loop produces no output for an arriving signal, it is said to be in the null position for that signal. (In *b*, the arrows drawn with dashed lines indicate the direction of signals for which the loop is at a null.)

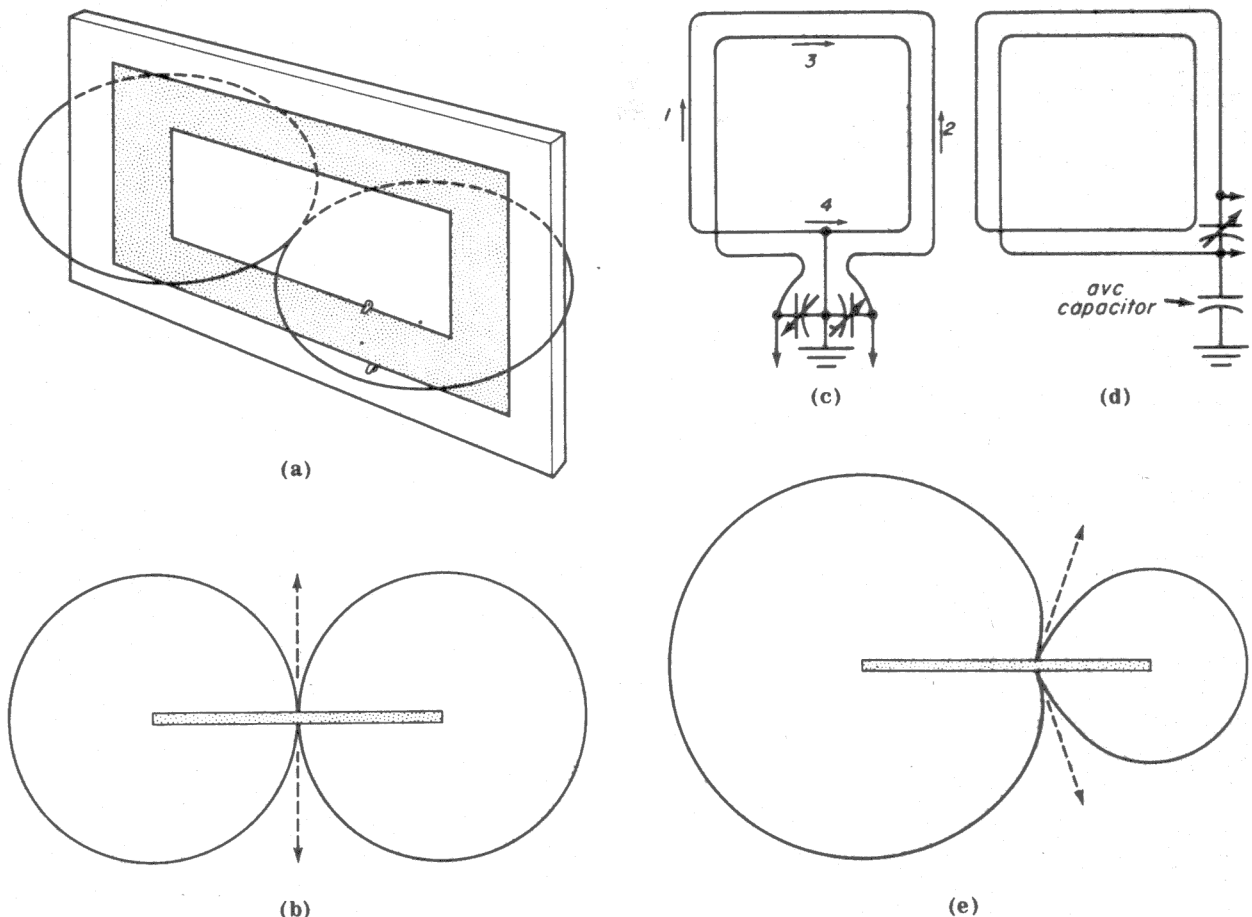


Fig. 32-24

The reason why such a loop produces no output for a broadside signal is that broadside signal induces currents which nullify each other, instead of reinforcing each other, in opposite branches of the loop. Thus, in *c*, the current shown by arrow 1 will buck, or cancel, the current represented by arrow 2. Similarly, the current represented by arrows 3 and 4 buck each other.

But if such a loop is turned end on to the arriving signal, the currents induced in the opposing vertical branches will be unequal, at any given instant, because one branch will be closer to the transmitter than the other. Suppose it is the branch shown at the left, in *c*. The arriving wavefront will reach the left branch and pass it before it reaches the right branch. Although it will induce equal currents in the two branches, there will be a phase difference between the currents — they will not be equal *at the same time*, because the wavefront did not

reach them at the same time, as it does when the loop is broadside to the line of travel. Since, at any instant, the currents are unequal, there will be a difference, or signal, voltage at the output terminals, at all instants of an r-f cycle.

The familiar loop used in home radio receivers is not a balanced loop. It is not center-grounded. It is connected as shown at *d*. One end is grounded for r.f. Consider it as two halves of a loop connected in series to produce a whole loop. The half between center point and r-f ground will be closer to ground potential for r-f signals than the half between the center point and the hot end. The latter half will have more pickup than the other half. The lobes will be unequal in size and shape. Their pattern will be something like that shown at *e*. Note that now the direction of null (or of minimum pickup, for there may not be a complete nullification) is no longer exactly at right angles to the plane of the loop. It is usually

not possible to get a complete null on a home receiver, though minimum pickup may be reasonably well defined.

A further effect that obscures the null position is the arrival of the same signal from two directions. It may come by a direct route, and it may come from overhead, due to refraction in the atmosphere. The latter effect is particularly noticeable at night when ionization conditions are often just right to produce it, and is called the *night effect*.

Since the loop cannot be in two different positions at one time, it cannot produce a null for both signals simultaneously. Consequently, the location of the null direction is vague.

Ferrite-Rod Antenna. Another type of indoor antenna makes use of the magnetic properties of iron. It is known as the ferrite-rod antenna. It consists of a coil of wire that is wound around a ferrite core (ferrite is powdered iron held together by a plastic binder). You recall that pure iron or soft iron becomes magnetized when it is placed within a coil of wire that is carrying an electric current. Moreover, soft iron is one of the most permeable of magnetic substances.

The powdered iron rod has two functions — it increases the Q of the winding and it acts as a rod antenna. When the rod is of approximately the same length as the coil, it doesn't pick up appreciably more energy than the coil does. But as the rod is made longer, even though the coil is kept at the same size, the pickup of the combination increases due to the increased area of rod intercepting a larger portion of the arriving wave-front. The alternations of the intercepted signal cause the magnetic

flux lines concentrated in the rod, and in the field around the rod, to alternate in magnetic polarity (north to south, south to north, north to south, and so on). As the changing flux lines are cut by the turns of the coil, they induce a current in the winding. Because of the very high Q and consequent high impedance of the resonant LC circuit, a high signal voltage is developed across the ends of the winding. Consequently, the antenna has high sensitivity for its relatively small size. When mounted vertically, the antenna responds to stations in all directions. However, this mounting reduces signal strength and tends to cause the antenna to pick up more noise from appliances in other apartments above it. When mounted horizontally, the antenna receives signals best when either end of the ferrite-rod is pointed in the direction of the station desired. The horizontal mounting allows the user to reduce the pickup of certain electrical noises by turning the horizontally-mounted antenna until its length is at right angles to the direction of the source of noise.

As shown in Fig. 32-25, ferrite-rod antennas come in several sizes, ranging from about $2\frac{1}{4}$ to 7 inches in length, with an average of $\frac{1}{2}$ inch in diameter. Because they are so very compact, they occupy little space, which makes them ideal for small receivers. The antenna shown in Fig. 32-25a is fixed but the one shown in Fig. 32-25b may be adjusted for maximum efficiency in receiving some desired station. That shown in Fig. 32-25c has the greatest length of ferrite-rod, which gives it the greatest capture area of the three that are shown. The greater the capture area, the greater is the signal pickup. There is a limit, however, to the increase in pickup for length of rod; the longest practical ferrite-rod being made at the time of writing is 7 inches.

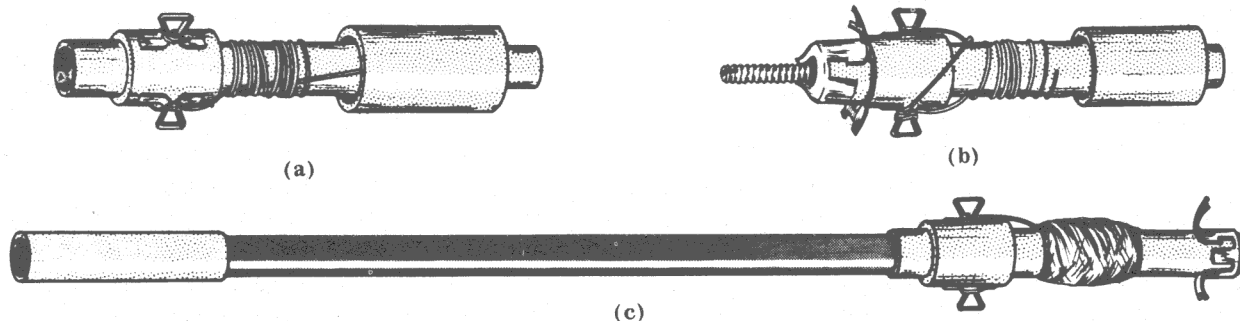


Fig. 32-25